

Longitudinal top polarization as a probe of a possible origin of forward-backward asymmetry of the top quark at the Tevatron

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If the forward-backward (FB) asymmetry of top quark (A_{FB}) observed at the Tevatron deviates from the SM prediction, there must be P -violating interactions in $q\bar{q} \rightarrow t\bar{t}$. This new interaction will necessarily affect the top spin polarization. In this letter, we perform a model independent analysis on the longitudinal (anti)top polarization (P_L and \bar{P}_L) using an effective lagrangian with dim-6 four-quark operators relevant for $q\bar{q} \rightarrow t\bar{t}$, and show that the P -odd observable corresponding to the polarization difference ($P_L - \bar{P}_L$) gives important informations on the chiral structures of new physics that might be relevant to the A_{FB} .

1. Top physics has entered a new era after its first discovery, due to the high luminosity achieved at the Tevatron and the launch of the Large Hadron Collider (LHC). Most recent results on the top mass and the $t\bar{t}$ production cross section (CDF and D0 Collaborations combined analysis) are : $m_t = (171.3 \pm 1.3)$ GeV and $\sigma_{t\bar{t}} = (7.50 \pm 0.48)$ pb, respectively [1]. Being the heaviest particle observed so far with its mass being near the electroweak breaking (EWSB) scale, the top sector might provide a new window to the EWSB mechanism. Precise determination of top quark properties is essential to address this issue, such as the top compositeness.

The forward-backward asymmetry A_{FB} of the top quark is one of the interesting observables related with top quark. Within the SM, this asymmetry vanishes at leading order in QCD because of C symmetry. At next-to-leading order [$O(\alpha_s^3)$], a nonzero A_{FB} can develop from the interference between the Born amplitude and two-gluon intermediate state, as well as the gluon bremsstrahlung and gluon-(anti)quark scattering into $t\bar{t}$, with the prediction $A_{\text{FB}} \sim 0.078$ [2]. The measured asymmetry has been off the SM prediction by 2σ for the last few years, albeit a large experimental uncertainties. The most recent measurement in the $t\bar{t}$ rest frame is [3]

$$A_{\text{FB}} \equiv \frac{N_t(\cos\theta \geq 0) - N_{\bar{t}}(\cos\theta \geq 0)}{N_t(\cos\theta \geq 0) + N_{\bar{t}}(\cos\theta \geq 0)} \quad (1)$$

$$= (0.158 \pm 0.072 \pm 0.017) \quad (2)$$

with θ being the polar angle of the top quark with respect to the incoming proton in the $t\bar{t}$ rest frame. The newest number is somewhat lower than the previous one [1], $A_{\text{FB}} = 0.24 \pm 0.13 \pm 0.04$, which had stimulated a lot of activities on possible new physics scenarios [4–25].

Since the central value of the A_{FB} is getting closer to the SM prediction, any new physics effects might be

smaller than had been thought previously. Also there is no clear signal for such a new resonance [1]. Therefore, it would be reasonable to assume a new physics scale relevant to A_{FB} is large enough so that production of a new particle is beyond the reach of the Tevatron [14], which makes a key difference between our work and other literatures. Then it is adequate to integrate out the heavy fields, and we can adopt a model independent effective lagrangian approach in order to study new physics effects on $\sigma_{t\bar{t}}$ and A_{FB} . If new physics scale is high enough, then their effects on the $t\bar{t}$ production at the Tevatron can be described by dim-6 effective lagrangian. Since the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry has been well established for the light quark system, we assume that $SU(2)_L \times U(1)_Y$ symmetry is linearly realized on the light quark system. And we impose the custodial symmetry $SU(2)_R$ for the light quark sector. Under these assumptions, the dimension-6 operators relevant to the $t\bar{t}$ production at the Tevatron are

$$\mathcal{L}_6 = \frac{g_s^2}{\Lambda^2} \sum_{A,B} [C_{1q}^{AB} (\bar{q}_A \gamma_\mu q_A) (\bar{t}_B \gamma^\mu t_B) + C_{8q}^{AB} (\bar{q}_A T^a \gamma_\mu q_A) (\bar{t}_B T^a \gamma^\mu t_B)] \quad (3)$$

where $T^a = \lambda^a/2$, $\{A, B\} = \{L, R\}$, and $L, R \equiv (1 \mp \gamma_5)/2$ with $q = (u, d)^T, (s, c)^T$ [37]. Our choice of dim-6 operators is basically the same as Ref. [26], except that we use the chiral basis for t and \bar{t} . This operator set could be used, for example, to study $t\bar{t}$ production at the Tevatron in case of the composite top scenarios [27].

Before we move to the main subject of this paper, we would like to make a comment on other dim-6 operators that involves t and \bar{t} . In principle, there are many more operators that involve t, \bar{t} and gluon field strength tensor $G_{\mu\nu}^a$, which have been studied recently in Refs [28] and

[29]. Many of them are however generated at one-loop level, unlike the operators we are considering here and in Ref. [14]. Therefore their effects would be further suppressed by a loop factor $1/(4\pi)^2$ and a power of strong coupling constant g_s , relative to the operators we study. Our choice of operators should be enough for the purpose

of $t\bar{t}$ production at the Tevatron.

Using the above effective lagrangian, we can calculate the cross section up to $O(1/\Lambda^2)$, keeping only the interference term between the standard model and new physics contributions. The squared amplitude summed (averaged) over the final (initial) spins and colors is given by

$$\overline{|\mathcal{M}|^2} \simeq \frac{4g_s^4}{9\hat{s}^2} \left\{ 2m_t^2 \hat{s} \left[1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right] s_{\hat{\theta}}^2 + \frac{\hat{s}^2}{2} \left[\left(1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right) (1 + c_{\hat{\theta}}^2) + \hat{\beta}_t \left(\frac{\hat{s}}{\Lambda^2} (C_1 - C_2) \right) c_{\hat{\theta}} \right] \right\} \quad (4)$$

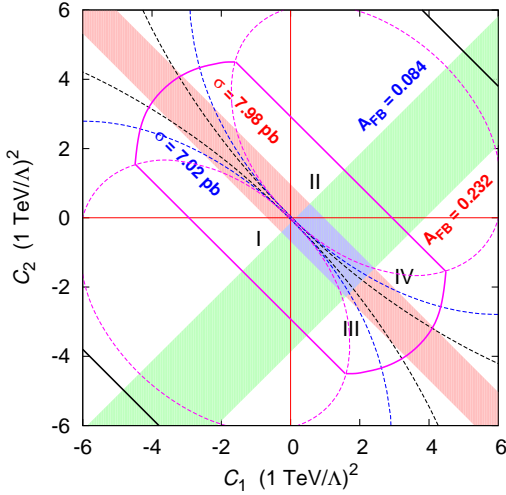


FIG. 1: The region in (C_1, C_2) plane that is consistent with the Tevatron data at the 1- σ level: $\sigma_{t\bar{t}} = (7.50 \pm 0.48)$ pb and $A_{\text{FB}} = (0.158 \pm 0.072 \pm 0.017)$. Also shown are the boundaries of the regions where our effective lagrangian description is valid. For details, we refer to Ref. [14].

where $\hat{s} = (p_1 + p_2)^2$, $\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}$, and $s_{\hat{\theta}} \equiv \sin \hat{\theta}$ and $c_{\hat{\theta}} \equiv \cos \hat{\theta}$ with $\hat{\theta}$ being the polar angle between the incoming quark and the outgoing top quark in the $t\bar{t}$ rest frame. And two couplings $C_{1,2}$ are defined as [38]

$$C_1 \equiv C_{8q}^{RR} + C_{8q}^{LL}, \quad C_2 \equiv C_{8q}^{LR} + C_{8q}^{RL}. \quad (5)$$

In our previous study [14], we performed a model independent study of $\sigma_{t\bar{t}}$ and A_{FB} considering the interference effects of the SM amplitude and the new physics amplitudes from dim-6 operators, the leading order operators in the effective lagrangian. Here we update the previous results in the light of the new measurement of A_{FB} , see Fig. 1. The main results of Ref. [14] can be summarized as follows in terms of two effective couplings C_1 and C_2 :

- $\Delta\sigma_{t\bar{t}} \equiv \sigma_{t\bar{t}} - \sigma_{t\bar{t}}^{\text{SM}} \propto (C_1 + C_2)$, whereas $\Delta A_{\text{FB}} \equiv A_{\text{FB}} - A_{\text{FB}}^{\text{SM}} \propto (C_1 - C_2)$, i.e., the new physics contributions to the total cross section and A_{FB} are

orthogonal. Therefore the new physics can change A_{FB} considerably without affecting $\sigma_{t\bar{t}}$ too much, as long as $C_1 + C_2 \approx 0$.

- In order to have nonzero new physics contribution to A_{FB} , we need $C_1 - C_2 \neq 0$. If parity were conserved in the light quark sector in dim-6 operators, one would have $C_{8q}^{LL} = C_{8q}^{RR}$, and $C_{8q}^{LR} = C_{8q}^{RL}$. If parity were conserved in the top quark sector, one would have $C_{8q}^{LL} = C_{8q}^{LR}$ and $C_{8q}^{RR} = C_{8q}^{RL}$. In either case, we end up with the vanishing condition: $(C_1 - C_2) = 0$. Therefore, in order to nonzero new physics contribution from dim-6 operators, one has to break parity P both in the light quark and the top quark sectors. This might be observable in (or constrained by) parity violating effects in nucleon nuclear scattering, for example.
- The usual spin-spin correlation C is strongly correlated with the top quark pair production cross section $\sigma_{t\bar{t}}$, and not with the A_{FB} . On the other hand, the newly defined FB spin-spin correlation C_{FB} is strongly correlated with the A_{FB} , and thus can be another important check of any anomaly in A_{FB} . If there is any deviation in A_{FB} , should there be some deviation in C_{FB} too.
- Since $\sigma_{t\bar{t}}$ and A_{FB} depend only on two combinations C_1 and C_2 , we can not know exactly the chiral structure of new physics from these two observables alone. We need another physical observables which are sensitive to independent combinations of coupling constants in dim-6 operators.

It is the purpose of this letter to present new observables which show different dependence on C_{8q}^{AB} 's from $\sigma_{t\bar{t}}$ and A_{FB} . What we propose is the longitudinal polarization of top quark, $P_L \equiv \langle \vec{S}_t \cdot \vec{n}_t \rangle$, where \vec{n}_t is any unit vector defining the spin quantization axis of the top quark, and similarly for the antitop: $\vec{P}_L \equiv \langle \vec{S}_{\bar{t}} \cdot \vec{n}_{\bar{t}} \rangle$. If we choose $\vec{n}_{t(\bar{t})} = \vec{p}_{t(\bar{t})}/|\vec{p}_{t(\bar{t})}|$ with $\vec{p}_{t(\bar{t})}$ being the momentum vector of $t(\bar{t})$, $P_L(\vec{P}_L)$ becomes the usual helicity of (anti)top quark. Any observables corresponding to the

longitudinal-polarization combinations ($P_L \pm \bar{P}_L$) vanish in QCD because of parity (P) conservation. On the other hand, if there is new physics that affects A_{FB} , parity is necessarily broken. Therefore one can expect nonzero P -violating polarization observables in general, which is the main point of the present work.

2. Now let us study the polarizations of t and \bar{t} at the Tevatron using the helicity amplitude method. In particular, we consider the polarization coefficients involving the longitudinal polarizations of t and \bar{t} which vanish in QCD due to its P conservation.

In the center-of-mass frame of the $t\bar{t}$ pair, the helicity amplitudes for the process $q(\lambda)\bar{q}(\bar{\lambda}) \rightarrow t(\sigma)\bar{t}(\bar{\sigma})$ induced by the dimension-6 operators, Eq. (3), and as well as the SM interactions are given by

$$\mathcal{M}(\sigma, \bar{\sigma}; \lambda, \bar{\lambda}) \equiv \frac{g_s^2}{\hat{s}} [\delta_{ij} \delta_{kl} \langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{\text{sing}} + T_{ij}^a T_{kl}^a \langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{\text{oct}}] \quad (6)$$

where we denote the helicities of the incoming quarks by λ and $\bar{\lambda}$ and those of the outgoing top quarks by σ and $\bar{\sigma}$, respectively, with $\lambda, \sigma = +$ and $-$ standing for right- and left-handed particles. The singlet amplitude $\langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{\text{sing}}$ is irrelevant in our case where we keep only the interference term between the SM and the new physics contributions. The octet amplitude $\langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{\text{oct}}$ can be written as

$$\langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{\text{oct}} \equiv \sum_{A,B=L,R} \left(1 + \frac{\hat{s}}{\Lambda^2} C_{8q}^{AB} \right) \langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{AB}^V \quad (7)$$

where the first and the second terms count for the contributions from the SM QCD and the dim-6 operators, respectively. The reduced amplitudes $\langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{AB}^V$ are explicitly given by

$$\begin{aligned} \langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{AB}^V &\equiv -\frac{m_t \sqrt{\hat{s}}}{2} (1 + A\lambda) \sigma s_{\hat{\theta}} \delta_{\lambda, -\bar{\lambda}} \delta_{\sigma, \bar{\sigma}} \\ &\quad - \frac{\hat{s}}{4} \left[(1 + A\lambda)(1 + \hat{\beta}_t B \sigma) c_{\hat{\theta}} \right. \\ &\quad \left. + (A + \lambda)(\hat{\beta}_t B + \sigma) \right] \delta_{\lambda, -\bar{\lambda}} \delta_{\sigma, -\bar{\sigma}}. \end{aligned} \quad (8)$$

The top-polarization weighted squared matrix elements can be computed from the helicity amplitudes by a suitable rotation [30] from the helicity basis to a general spin basis:

$$|\overline{\mathcal{M}}|^2 = \frac{2}{9} \frac{g_s^4}{\hat{s}^2} \sum_{\lambda, \bar{\lambda}} \left\{ \text{Tr}[\langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{\text{oct}} \bar{\rho}^T \langle \sigma, \bar{\sigma}; \lambda, \bar{\lambda} \rangle_{\text{oct}}^\dagger \rho] \right\} \quad (9)$$

where ρ and $\bar{\rho}$ are 2×2 polarization density matrices for the top and anti-top, respectively:

$$\rho = \frac{1}{2} \begin{pmatrix} 1 + P_L & P_T e^{-i\alpha} \\ P_T e^{i\alpha} & 1 - P_L \end{pmatrix},$$

$$\bar{\rho} = \frac{1}{2} \begin{pmatrix} 1 + \bar{P}_L & -\bar{P}_T e^{i\bar{\alpha}} \\ -\bar{P}_T e^{-i\bar{\alpha}} & 1 - \bar{P}_L \end{pmatrix}. \quad (10)$$

Here, P_L and \bar{P}_L are the longitudinal polarizations of t and \bar{t} , respectively, while P_T and \bar{P}_T the degrees of transverse polarization with α and $\bar{\alpha}$ being the azimuthal angles with respect to the $t\bar{t}$ production plane.

Neglecting the transverse polarizations, an expansion of the trace in Eq. (9) leads to

$$|\overline{\mathcal{M}}|^2 = \frac{g_s^4}{\hat{s}^2} \left\{ \mathcal{D}_0 + \mathcal{D}_1(P_L + \bar{P}_L) + \mathcal{D}_2(P_L - \bar{P}_L) + \mathcal{D}_3 P_L \bar{P}_L \right\}. \quad (11)$$

The polarization coefficients \mathcal{D}_i ($i = 0 - 3$) are defined in terms of the octet helicity amplitudes by

$$\begin{aligned} \mathcal{D}_0 &= \frac{2}{9} \cdot \frac{1}{4} \sum_{\lambda, \bar{\lambda}} \left(|\langle ++; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 + |\langle --; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 \right. \\ &\quad \left. + |\langle +--; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 + |\langle -+; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 \right), \\ \mathcal{D}_1 &= \frac{2}{9} \cdot \frac{1}{4} \sum_{\lambda, \bar{\lambda}} \left(|\langle ++; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 - |\langle --; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 \right), \\ \mathcal{D}_2 &= \frac{2}{9} \cdot \frac{1}{4} \sum_{\lambda, \bar{\lambda}} \left(|\langle +--; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 - |\langle -+; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 \right), \\ \mathcal{D}_3 &= \frac{2}{9} \cdot \frac{1}{4} \sum_{\lambda, \bar{\lambda}} \left(|\langle ++; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 + |\langle --; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 \right. \\ &\quad \left. - |\langle +--; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 - |\langle -+; \lambda \bar{\lambda} \rangle_{\text{oct}}|^2 \right) \quad (12) \end{aligned}$$

The unpolarized coefficient \mathcal{D}_0 gives the squared amplitude summed (averaged) over the final (initial) spins and colors and one may obtain the same expression as Eq. (4) by keeping the terms up to $O(1/\Lambda^2)$ in \mathcal{D}_0 . So, the unpolarized coefficient \mathcal{D}_0 leads to the total cross section $\sigma_{t\bar{t}}$ and the forward-backward asymmetry A_{FB} . On the other hand, the coefficient \mathcal{D}_3 gives the spin-spin correlations C and C_{FB} considered and suggested before.

Note that the other two coefficients \mathcal{D}_1 and \mathcal{D}_2 are P violating. Furthermore, the coefficient \mathcal{D}_1 is odd under both the CP and CPT transformations [39]. In our effective lagrangian approach, new heavy particles are integrated out, and there is no new strong CP-even phase, and so \mathcal{D}_1 is zero. However, it could be nonzero when the heavy particle is explicitly included, and we keep the finite decay width of the heavy particle together with possible CP-violating phases in its couplings to light and top quarks. This issue will be discussed in full in the future publication [31].

The other P -violating coefficient \mathcal{D}_2 could be observable at the Tevatron, revealing genuine features of new

physics responsible for A_{FB} . Explicitly, we have obtained

$$\mathcal{D}_2 \simeq \frac{\hat{s}}{9\Lambda^2} \left[(C'_1 + C'_2) \hat{\beta}_t (1 + c_\theta^2) + (C'_1 - C'_2) (5 - 3\hat{\beta}_t^2) c_\theta \right] \quad (13)$$

with

$$C'_1 \equiv C_{8q}^{RR} - C_{8q}^{LL}, \quad C'_2 \equiv C_{8q}^{LR} - C_{8q}^{RL}. \quad (14)$$

Therefore \mathcal{D}_2 will provide additional information on the chiral structure of new physics in $q\bar{q} \rightarrow t\bar{t}$. When we integrate over the polar angle $\hat{\theta}$, only the first term involving

$$(C'_1 + C'_2) = C_{8q}^{RR} - C_{8q}^{LL} + C_{8q}^{LR} - C_{8q}^{RL}$$

survives. On the other hand, if we separate the forward and the backward top samples and take the difference, the orthogonal combination in the second term survives:

$$(C'_1 - C'_2) = C_{8q}^{RR} - C_{8q}^{LL} - C_{8q}^{LR} + C_{8q}^{RL}.$$

For definiteness, we consider the two new observables:

$$D \equiv \frac{\sigma(t_R \bar{t}_L) - \sigma(t_L \bar{t}_R)}{\sigma(t_R \bar{t}_R) + \sigma(t_L \bar{t}_L) + \sigma(t_L \bar{t}_R) + \sigma(t_R \bar{t}_L)},$$

$$D_{\text{FB}} \equiv D(\cos \hat{\theta} \geq 0) - D(\cos \hat{\theta} \leq 0) \quad (15)$$

which involve the sum and difference of the coefficients C'_1 and C'_2 , respectively. In Fig. 2, we show the P -violating spin correlations D and D_{FB} in the (C'_1, C'_2) plane. We observe that $|D|$ and $|D_{\text{FB}}|$ could be as large as 0.1 in the region $|C'_{1,2}| (1 \text{ TeV}/\Lambda)^2 \lesssim 1$ which can be observed with an event sample of about 100 $t\bar{t}$ pairs after event selection cuts. Note that there are no experimental constraints on the D and D_{FB} observables yet, but they can be measured with a statistical precision of $\sim 5\%$ using the full anticipated Tevatron data set of 10 fb^{-1} [32].

In principle, the polarization coefficients could be measured by studying the angular distributions of the top-quark decay products. The top and anti-top quarks decay into two b quarks and two W bosons. When both of the W bosons decay leptonically, in the helicity basis, the amplitude squared can be written as

$$\begin{aligned} |\overline{\mathcal{M}}|^2 = \frac{g_s^4}{\hat{s}^2} & \left\{ \mathcal{D}_0 + \mathcal{D}_1 (\cos \theta_+^* + \cos \theta_-^*) \right. \\ & \left. + \mathcal{D}_2 (\cos \theta_+^* - \cos \theta_-^*) + \mathcal{D}_3 \cos \theta_+^* \cos \theta_-^* \right\} 16 \end{aligned}$$

where θ_+^* (θ_-^*) is the angle between the charged lepton l^+ (l^-) in the top (anti-top) rest frame and the direction of the top (anti-top) in the $t\bar{t}$ rest frame. The M_{T2} variable could be useful to reconstruct the $t\bar{t}$ rest frame even with the two missing neutrinos, which deserves a further study in the future.

3. Now we study specific new physics that could generate the relevant dim-6 operators with corresponding

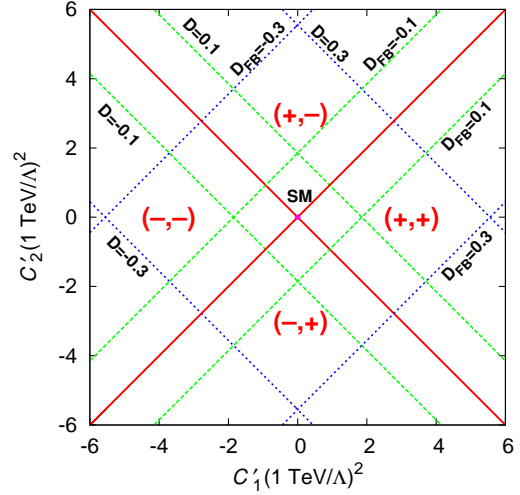


FIG. 2: The P -violating spin correlations D and D_{FB} in the (C'_1, C'_2) plane. The signs of (D, D_{FB}) are denoted.

Wilson coefficients. It is impossible to exhaust all the possibilities, and we consider the following interactions of quarks with spin-1 flavor-conserving (FC) color-octet V_{8A}^a vectors, spin-1 flavor-violating (FV) color-singlet \tilde{V}_{1A}^a and color-octet \tilde{V}_{8A}^a vectors, and spin-0 FV color-singlet \tilde{S}_1 and color-octet \tilde{S}_{8A}^a scalars ($A = L, R$):

$$\begin{aligned} \mathcal{L}_{\text{int}} = & g_s \sum_A V_{8A}^{a\mu} [g_{8q}^A (\bar{q}_A \gamma_\mu T^a q_A) + g_{8t}^A (\bar{t}_A \gamma_\mu T^a t_A)] \\ & + g_s \sum_A [\tilde{V}_{1A}^\mu \tilde{g}_{1q}^A (\bar{t}_A \gamma_\mu q_A) + \tilde{V}_{8A}^\mu \tilde{g}_{8q}^A (\bar{t}_A \gamma_\mu T^a q_A) + \text{h.c.}] \\ & + g_s \sum_A [\tilde{S}_{1A} \tilde{\eta}_{1q}^A (\bar{t}_A q) + \tilde{S}_{8A} \tilde{\eta}_{8q}^A (\bar{t}_A T^a q) + \text{h.c.}], \quad (17) \end{aligned}$$

where q denotes light quarks (either u or d depending on the models). This interaction lagrangian encompasses many models beyond the SM, and make a good starting point to study the underlying mechanism for the effective lagrangian discussed earlier. If the spin-1 particle has both the FC and FV interactions, we may set $V_8^\mu = \tilde{V}_8^\mu$.

After integrating out the heavy vector and scalar fields, we obtain the Wilson coefficients as follows:

$$\begin{aligned} \frac{C_{8q}^{RR}}{\Lambda^2} &= -\frac{g_{8q}^R g_{8t}^R}{m_{V_{8R}}^2} - \frac{2|\tilde{g}_{1q}^R|^2}{m_{\tilde{V}_{1R}}^2} + \frac{1}{N_C} \frac{|\tilde{g}_{8q}^R|^2}{m_{\tilde{V}_{8R}}^2}, \\ \frac{C_{8q}^{LL}}{\Lambda^2} &= -\frac{g_{8q}^L g_{8t}^L}{m_{V_{8L}}^2} - \frac{2|\tilde{g}_{1q}^L|^2}{m_{\tilde{V}_{1L}}^2} + \frac{1}{N_C} \frac{|\tilde{g}_{8q}^L|^2}{m_{\tilde{V}_{8L}}^2}, \\ \frac{C_{8q}^{LR}}{\Lambda^2} &= -\frac{g_{8q}^L g_{8t}^R}{m_{V_8}^2} - \frac{|\tilde{\eta}_{1q}^L|^2}{m_{\tilde{S}_{1L}}^2} + \frac{1}{2N_C} \frac{|\tilde{\eta}_{8q}^L|^2}{m_{\tilde{S}_{8L}}^2}, \\ \frac{C_{8q}^{RL}}{\Lambda^2} &= -\frac{g_{8q}^R g_{8t}^L}{m_{V_8}^2} - \frac{|\tilde{\eta}_{1q}^R|^2}{m_{\tilde{S}_{1R}}^2} + \frac{1}{2N_C} \frac{|\tilde{\eta}_{8q}^R|^2}{m_{\tilde{S}_{8R}}^2}, \end{aligned} \quad (18)$$

where $m_{V_{8R,8L}}$ ($m_{\tilde{V}_{iR,iL}}$) and $m_{\tilde{S}_{iR,iL}}$ denote the masses of vectors $V_{8R,8L}$ ($\tilde{V}_{iR,iL}$) and scalars $\tilde{S}_{iR,iL}$, respectively,

with $i = 1, 8$. Note that the contributions to the coefficients C_{8q}^{LR} and C_{8q}^{RL} from the FC color-octet vectors may not be vanishing in the coexistence of V_{8R} and V_{8L} and in this case we take $m_{V_{8R}} = m_{V_{8L}} = m_{V_8}$.

Another interesting possibility is minimal flavor violating interactions of color-triplet S_k^γ with mass m_{S_3} and color-sextet scalars $S_{ij}^{\alpha\beta}$ with mass m_{S_6} with the SM quarks [33]. Here α, β, γ and i, j, k are color and flavor indices, respectively. For example, if we consider the following interactions (Model V and VI in Ref. [33]),

$$\mathcal{L} = g_s \left[\frac{\eta_3}{2} \epsilon_{\alpha\beta\gamma} \epsilon^{ijk} u_{iR}^\alpha u_{jR}^\beta S_k^\gamma + \eta_6 u_{iR}^\alpha u_{jR}^\beta S_{ij}^{\alpha\beta} + h.c. \right] \quad (19)$$

the u -channel exchange of new scalars can contribute to $u\bar{u} \rightarrow t\bar{t}$, resulting in [40]

$$\frac{C_{8u}^{RR}}{\Lambda^2} = -\frac{|\eta_3|^2}{m_{S_3}^2} + \frac{2|\eta_6|^2}{m_{S_6}^2}. \quad (20)$$

Since these new scalars couple only to the right-handed up-type quarks, constraints on the couplings η_3 and η_8 from flavor physics are rather weak, and one can accommodate the observed A_{FB} easily.

In Table I, we show the new particle exchanges under consideration and the signs of the couplings induced by them. Note that the particle exchanges with $(C_1 - C_2) > 0$ are preferred by the positive A_{FB} at the 1- σ level.

4. Let us first consider the FV cases. Among the FV interactions with vector or scalar bosons, $\tilde{V}_{8R,8L}$, $\tilde{S}_{1R,1L}$, and $S_{13}^{\alpha\beta}$ can give the correct sign for $(C_1 - C_2)$ [14]. But one can not discriminate one model from another only with the A_{FB} measurement. From Table I, we observe that each of the four cases with \tilde{V}_{8R} , \tilde{V}_{8L} , \tilde{S}_{1R} , and \tilde{S}_{1L} gives a different sign combination of $C'_1 + C'_2$ and $C'_1 - C'_2$. Therefore, a simple sign measurement of D and D_{FB} can endow us with the model-discriminating power. In Fig. 3, we show the prediction of each model for D and D_{FB} varying the model parameters over the ranges:

$$\begin{aligned} \tilde{V}_{8R,8L} &: \frac{1}{N_c} \left(\frac{1 \text{ TeV}}{m_{\tilde{V}_{8R,8L}}} \right)^2 |\tilde{g}_{8q}^{R,L}|^2 \simeq 0.56 \pm 0.41, \\ \tilde{S}_{1R,1L} &: \left(\frac{1 \text{ TeV}}{m_{\tilde{S}_{1R,1L}}} \right)^2 |\tilde{\eta}_{1q}^{R,L}|^2 \simeq 0.41 \pm 0.26, \\ S_{13}^{\alpha\beta} &: 2 \left(\frac{1 \text{ TeV}}{m_{S_6}} \right)^2 |\eta_6|^2 \simeq 0.56 \pm 0.41. \end{aligned} \quad (21)$$

which are consistent with the current measurements of $\sigma_{t\bar{t}}$ and A_{FB} at the 1- σ level (see Fig. 1). We observe that D and D_{FB} take the same $(+, +)$ and $(-, -)$ signs for \tilde{V}_{8R} and \tilde{V}_{8L} , respectively, while they take the different $(+, -)$ and $(-, +)$ signs for \tilde{S}_{1L} and \tilde{S}_{1R} , respectively. The color-sextet scalar $S_{13}^{\alpha\beta}$ gives the same $(+, +)$ sign as the \tilde{V}_{8R} case.

Unlike the FV cases, the FC color-octet vectors can always accommodate the positive sign of $(C_1 - C_2)$. For

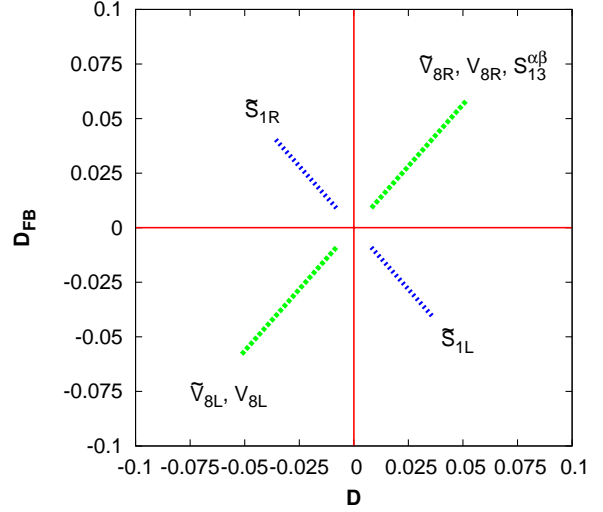


FIG. 3: The predictions for D and D_{FB} of the models under consideration, being consistent with the $\sigma_{t\bar{t}}$ and A_{FB} measurements at the 1- σ level. We assume only one resonance exists or dominates.

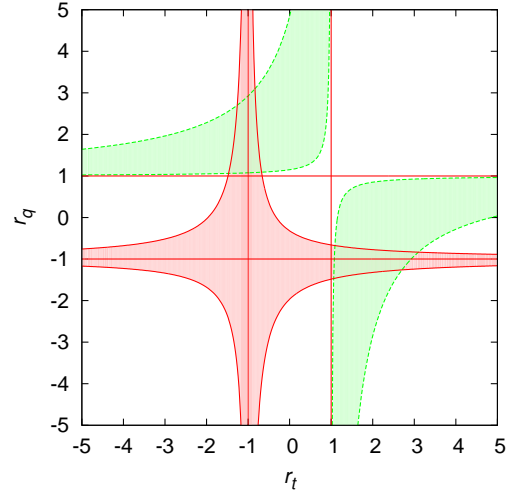


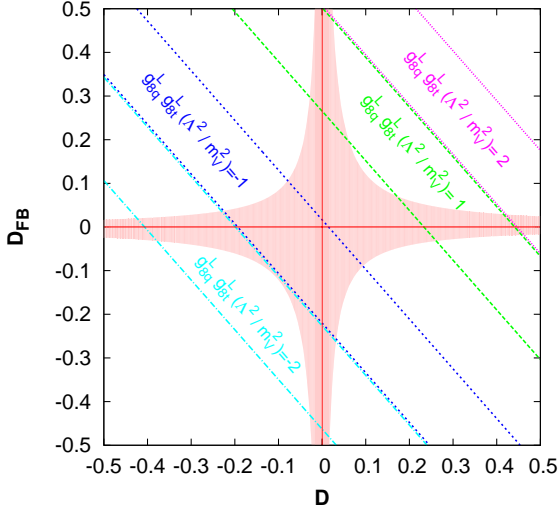
FIG. 4: The region in (r_t, r_q) plane that is consistent with the Tevatron $\sigma_{t\bar{t}}$ (red) and A_{FB} (green) measurements at the 1- σ level. The general flavor-conserving case is considered taking $g_{8q}^L g_{8t}^L (1 \text{ TeV}/m_{V_8})^2 = +1$.

the case of V_{8R} (V_{8L}), the couplings g_{8q}^R (g_{8q}^L) and g_{8t}^R (g_{8t}^L) must have different signs to accommodate the positive A_{FB} . In Fig. 3, we also show the predictions of the model with V_{8R} or V_{8L} vector for D and D_{FB} .

5. Up to now, we have only one type of couplings by assuming that only one resonance contributes to the $t\bar{t}$ production at the Tevatron. However, the flavor-conserving color-octet V_{8R} and V_{8L} vectors can coexist in general, and then the situation could be more complicated. In such a general case, all the four couplings C^{RR} , C^{LL} , C^{LR} , and C^{RL} could be nonzero, in contrast to the

TABLE I: New particle exchanges and the signs of induced couplings C^{AB} ($A, B = R, L$), $C_1 - C_2$, $C'_1 + C'_2$, and $C'_1 - C'_2$.

Resonance	C^{RR}	C^{LL}	C^{LR}	C^{RL}	$C_1 - C_2$	$C'_1 + C'_2$	$C'_1 - C'_2$	A_{FB}
\tilde{V}_{1R}	−	0	0	0	−	−	−	×
\tilde{V}_{1L}	0	−	0	0	−	+	+	×
\tilde{V}_{8R}	+	0	0	0	+	+	+	✓
\tilde{V}_{8L}	0	+	0	0	+	−	−	✓
\tilde{S}_{1R}	0	0	0	−	+	+	−	✓
\tilde{S}_{1L}	0	0	−	0	+	−	+	✓
\tilde{S}_{8R}	0	0	0	+	−	−	+	×
\tilde{S}_{8L}	0	0	+	0	−	+	−	×
S_2^α	−	0	0	0	−	−	−	×
$S_{13}^{\alpha\beta}$	+	0	0	0	+	+	+	✓
V_{8R}	±	0	0	0	±	±	±	✓(+) or ×(−)
V_{8L}	0	±	0	0	±	∓	∓	✓(+) or ×(−)
V_{8R}, V_{8L}	indef.	indef.	indef.	indef.	indef.	indef.	indef.	indef.

FIG. 5: The predictions for D and D_{FB} , being consistent with the $\sigma_{t\bar{t}}$ and A_{FB} measurements at the $1\text{-}\sigma$ level, for several values of $g_{8q}^L g_{8t}^L (1 \text{ TeV}/m_{V8})^2 = +2$ (magenta), $+1$ (green), -1 (blue), and -1 (sky blue), from the upper-right corner to the lower-left one. The general model with flavor-conserving color-octet V_{8R} and V_{8L} vectors is considered.

previous one-coupling cases. In this case, the sum and differences of the couplings can be reparametrized as

$$\begin{aligned} (C_1 + C_2)/\Lambda^2 &= -g_{8q}^L g_{8t}^L (r_q + 1)(r_t + 1)/m_{V8}^2 \\ (C_1 - C_2)/\Lambda^2 &= -g_{8q}^L g_{8t}^L (r_q - 1)(r_t - 1)/m_{V8}^2 \end{aligned}$$

$$\begin{aligned} (C'_1 + C'_2)/\Lambda^2 &= -g_{8q}^L g_{8t}^L (r_q + 1)(r_t - 1)/m_{V8}^2 \\ (C'_1 - C'_2)/\Lambda^2 &= -g_{8q}^L g_{8t}^L (r_q - 1)(r_t + 1)/m_{V8}^2 \end{aligned} \quad (22)$$

with $r_q \equiv g_{8q}^R/g_{8q}^L$ and $r_t \equiv g_{8t}^R/g_{8t}^L$. Any deviation of r_q (r_t) from 1 characterizes P violation in the light (top) quark sector. In Fig. 4, we show the $1\text{-}\sigma$ region in (r_t, r_q) plane taking $g_{8q}^L g_{8t}^L (1 \text{ TeV}/m_{V8})^2 = +1$. We observe the consistent region lies along the line $r_t = -1$ ($r_q = -1$) with $1 < r_q \lesssim 3$ ($1 < r_t \lesssim 3$). When $g_{8q}^L g_{8t}^L (1 \text{ TeV}/m_{V8})^2 = -1$, one may have obtain similar results, except that the green region consistent with A_{FB} would be reflected with respect to the $r_q = 1$ line. In Fig. 5, we show the predictions of the general model with V_{8R} and V_{8L} for D and D_{FB} taking $g_{8q}^L g_{8t}^L (1 \text{ TeV}/m_{V8})^2 = \pm 1, \pm 2$. Note that the experimental measurements on the $\sigma_{t\bar{t}}$ and A_{FB} constrains the product of D and D_{FB} independently of $g_{8q}^L g_{8t}^L (\Lambda/m_{V8})^2$. This can be easily understood by observing the relation $(C_1 + C_2)(C_1 - C_2) = (C'_1 + C'_2)(C'_1 - C'_2)$ which leads to

$$\Delta\sigma_{t\bar{t}} \Delta A_{FB} \propto D D_{FB}. \quad (23)$$

Let us note that $\Delta\sigma_{t\bar{t}} \propto (C_1 + C_2)$, $\Delta A_{FB} \propto (C_1 + C_2)$, $D \propto (C'_1 + C'_2)$, and $D_{FB} \propto (C'_1 - C'_2)$. Furthermore, we observe

$$\begin{aligned} &g_{8q}^L g_{8t}^L \left(\frac{\Lambda}{m_{V8}} \right)^2 \\ &= \frac{[(C'_1 + C'_2) - (C_1 + C_2)][(C'_1 + C'_2) - (C_1 - C_2)]}{4(C'_1 + C'_2)} \end{aligned} \quad (24)$$

$$= \frac{1}{4} [(C'_1 + C'_2) - (C_1 + C_2) - (C_1 - C_2) + (C'_1 - C'_2)],$$

where, for the last term, the relation $(C_1 + C_2)(C_1 - C_2) = (C'_1 + C'_2)(C'_1 - C'_2)$ is used. This explains the linear dependence of D and D_{FB} on $g_{8q}^L g_{8t}^L (\Lambda/m_{V8})^2$ with some finite range coming from the current 1- σ experimental errors on $\sigma_{t\bar{t}}$ and A_{FB} , as shown in Fig. 5. We see that one of $|D|$ and $|D_{\text{FB}}|$ could be as large as ~ 1 when the other one is very small, while both of them could be ~ 0.1 simultaneously.

6. In this letter, we extended the model independent study of $t\bar{t}$ productions at the Tevatron using dimension-6 contact interactions relevant to $q\bar{q} \rightarrow t\bar{t}$, mainly concentrating on the longitudinal (anti)top polarization of P_L and \bar{P}_L in the helicity frame. As emphasized in Ref. [14], new physics affecting the Tevatron A_{FB} necessarily breaks parity unlike QCD. Then the P -odd top-quark longitudinal polarization observables can be nonzero, in sharp contrast to the case of pure QCD. Therefore, nonvanishing longitudinal polarization observables will be another important aspect of P -violating new physics relevant to $q\bar{q} \rightarrow t\bar{t}$. Most importantly, the longitudinal polarization of (anti)top quark can give another important clue for the chiral structure of new physics, which is completely independent of $\sigma_{t\bar{t}}$ or A_{FB} .

Using the conditions for the couplings of four-quark operators that could generate the FB asymmetry observed at the Tevatron (with the updated data on A_{FB}) [14], we studied the possible ranges of longitudinal (anti)top polarization, and their correlations with $\sigma_{t\bar{t}}$ and A_{FB} . Then we considered the s -, t - and u -channel exchanges of spin-0 and spin-1 particles whose color quantum number is either singlet, octet, triplet or sextet. Our results in Table I encode the predictions for the P -odd observables corresponding to the polarization difference ($P_L - \bar{P}_L$) in various new physics scenarios in a compact and an effective way, when those new particles are too heavy to be produced at the Tevatron but still affect A_{FB} . If these new particles could be produced directly at the Tevatron or at the LHC, we cannot use the effective lagrangian any more. We have to study specific models case by case including the new particles explicitly, and anticipate rich phenomenology at colliders as well as at low energy. Detailed study of these issues lies beyond the scope of this letter, and will be discussed in the future publications [31].

Note Added: While we were finishing this paper, we received three preprints [34–36] which also consider the observables related with the (anti)top polarization. In our work, we note that parity violation is crucial for new physics to make nonzero contributions to A_{FB} , and the longitudinal polarization of (anti)top quark can give another important clue for the chiral structure of new physics.

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- [37] Although we assume the $SU(2)_L \times SU(2)_R$ chiral symmetry for light quarks, all the explicit models do not satisfy this condition. In that case, one can interpret $q = u, d, s, c, b$.
- [38] Throughout this work, unless explicitly written, we are taking $C_{sq}^{AB} = C_{su}^{AB} = C_{sd}^{AB}$ assuming the $SU(2)_L \times SU(2)_R$ chiral symmetry. Under this assumption, the down-quark contribution to $\sigma_{t\bar{t}}$ and A_{FB} is suppressed relative to the up-quark one by a factor more than ~ 6 at the Tevatron.
- [39] The \bar{T} transformation reverses the signs of the spins and the three-momenta of the asymptotic states, without interchanging initial and final states, and the matrix element gets complex conjugated.
- [40] C_{1q}^{RR} is also induced by color-triplet and sextet scalars, but is not shown, since it is irrelevant here.